

**Total Maximum Daily Load of  
Phosphorus to  
Lake Habeeb,  
Allegany County, MD**

Prepared by:

Maryland Department of the Environment

2500 Broening Highway  
Baltimore, MD 21224

Submitted to:

Water Protection Division  
U.S. Environmental Protection Agency, Region III

1650 Arch Street  
Philadelphia, PA 19103-2029

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## **PREFACE**

Section 303(d) of the federal Clean Water Act directs States to identify and list waters, known as water quality limited segments (WQLSs), in which current required controls of a specified substance are inadequate to achieve water quality standards. For each WQLS, the State is to establish a Total Maximum Daily Load (TMDL) of the specified substance that the water can receive without violating water quality standards.

On the basis of water quality problems associated with nutrients, Lake Habeeb was identified on Maryland's 1998 list of WQLSs as being impaired. This report proposes the establishment of a TMDL for Lake Habeeb for phosphorus.

Once the TMDL is approved by the United States Environmental Protection Agency (EPA), it will be incorporated into the State's Continuing Planning Process. In the future, the established TMDL will support reservoir restoration and nonpoint source control measures needed to restore water quality in Lake Habeeb.

## **EXECUTIVE SUMMARY**

On the basis of water quality problems associated with nutrients, Lake Habeeb in the Evitts Creek watershed (2141002) was identified on Maryland's 1998 list of WQLSs as being impaired. This document establishes a Total Maximum Daily Load (TMDL) for the nutrient phosphorus entering Lake Habeeb.

Lake Habeeb is an impoundment located in Rocky Gap State Park, in Allegany County, Maryland. The impoundment lies on Rocky Gap Run, a tributary of the Evitts Creek. The watershed lies in a valley between Evitts and Martin Mountains. Lake Habeeb is a highly used recreational facility, with a major resort, conference center and Jack Nicklaus-designed golf course at the south end of the lake.

The death and decay of excessive algae can cause violations of the water quality standard for dissolved oxygen (DO), which can result in a disruption of the lake's ecosystem balance and cause fish kills. Analysis suggests that phosphorus is the limiting nutrient for the production of algae in Lake Habeeb.

The water quality goal of this TMDL is to reduce long-term phosphorus loads to an acceptable level consistent with the physical characteristics of Lake Habeeb. This reduced loading rate is predicted to resolve nuisance problems and maintain a dissolved oxygen concentration above the State water quality standard. The TMDL for phosphorus was determined using an empirical method known as the Vollenweider Relationship.

The average annual TMDL for phosphorus is about 930 lb/yr. There are no point sources in the Habeeb basin. Consequently, the allocation is partitioned between nonpoint sources and the margin of safety.

Preliminary estimations of the phosphorus controls necessary to achieve the load reduction were conducted to provide a reasonable assurance that the TMDL could be implemented. It is estimated that a 24% reduction in phosphorus loads would be necessary to meet the TMDL for phosphorus.

## **1.0 INTRODUCTION**

The Clean Water Act Section 303(d)(1)(C) and federal regulation 40 CFR 130.7(c)(1) direct each state to develop a Total Maximum Daily Load (TMDL) for all impaired waters on their Section 303(d) list. A TMDL reflects the maximum pollutant loading of an impairing substance a water body can receive and still meet water quality standards. A TMDL can be expressed in mass per time, toxicity, or any other appropriate measure (40 CFR 130.2(i)). TMDLs must take into account seasonal variations and a margin of safety (MOS) to allow for uncertainty. Maryland's 1998 303(d) list, submitted to EPA by the Maryland Department of the Environment (MDE), lists Lake Habeeb for nutrients. The 1998 listing was prompted by an assessment of data associated with Lake Habeeb (*Maryland Lake Water Assessment Report*, Maryland Department of Natural Resources (MDDNR), March 1998).

## **2.0 SETTING AND WATER QUALITY DESCRIPTION**

### **2.1 General Setting and Source Assessment**

Lake Habeeb is an impoundment located in Rocky Gap State Park, in Allegany County, Maryland (Figure 1). The watershed lies in a valley between Evitts and Martin Mountains. The impoundment, which is owned by Maryland Department of Natural Resources, lies on Rocky Gap Run, a tributary of the Evitts Creek. An earthen dam was installed for the purpose of recreational uses in 1969. Rocky Gap State park has swimming, hunting, camping, boat launching facilities, and is stocked with walleye, striped bass hybrids, smallmouth bass, and trout (DNR 1985). A major resort and conference center has been constructed at the south end of the lake, including a Jack Nicklaus signature golf course.

The Lake Habeeb watershed lies in the Allegheny Plateau. Evitts Mountain is located east of the watershed and Martin Mountain lies west of the watershed. Soils are formed in material weathered from limestone, sandstone, shale and siltstone. The soils in the watershed are in the Elliber-Dekalb-Opequon Association. The Elliber soils are on top and sides of the ridges and are deep over cherty limestone, and contain large quantities of chert fragments. The Dekalb soils are moderately deep over sandstone and are mostly very stony. The Opequon soils are generally on the sides of the limestone ridges (U.S. Department of Agriculture, Soil Survey of Allegany County, 1977).

Inflow to the lake is primarily via Rocky Gap Run, located primarily in Rocky Gap State Park, and two unnamed tributaries flowing down from the mountains. Discharge from the lake is to Evitts Creek. The watershed map (Figure 2) shows that land use in the watershed draining to Lake Habeeb is predominantly forested/herbaceous. Land use distribution in the watershed is approximately 80% forested/herbaceous, 9% developed, 7% agricultural and 4% water (Figure 3).

The load reduction assessment uses Chesapeake Bay Program data to estimate the nonpoint source loading rates, which represent the cumulative impact from all sources—naturally-occurring and human-induced. Natural background sources of phosphorus are included in the

assessment including direct atmospheric deposition to the water surface. The loads associated with each land use category include the naturally occurring as well as the human-induced contributions. No point source discharge permits for nutrients have been issued in the Lake Habeeb Watershed.

Several relevant statistics for Lake Habeeb are provided below in Table 1.

**Table 1**  
**Current Physical Characteristics of Lake Habeeb**

Location:	Allegany County, MD lat. 39° 42' 01" long. 78° 39' 42"
Surface Area:	208.5 acres
Length:	1. 76 mi
Maximum Width:	2100 feet
Average Lake Depth:	25.8 feet
Maximum Depth:	82 feet
Volume of Lake:	5,381 acre-feet (6,637,463 m <sup>3</sup> )
Drainage Area to Lake:	8.8 mi <sup>2</sup>
Average Discharge:	11.93 cfs

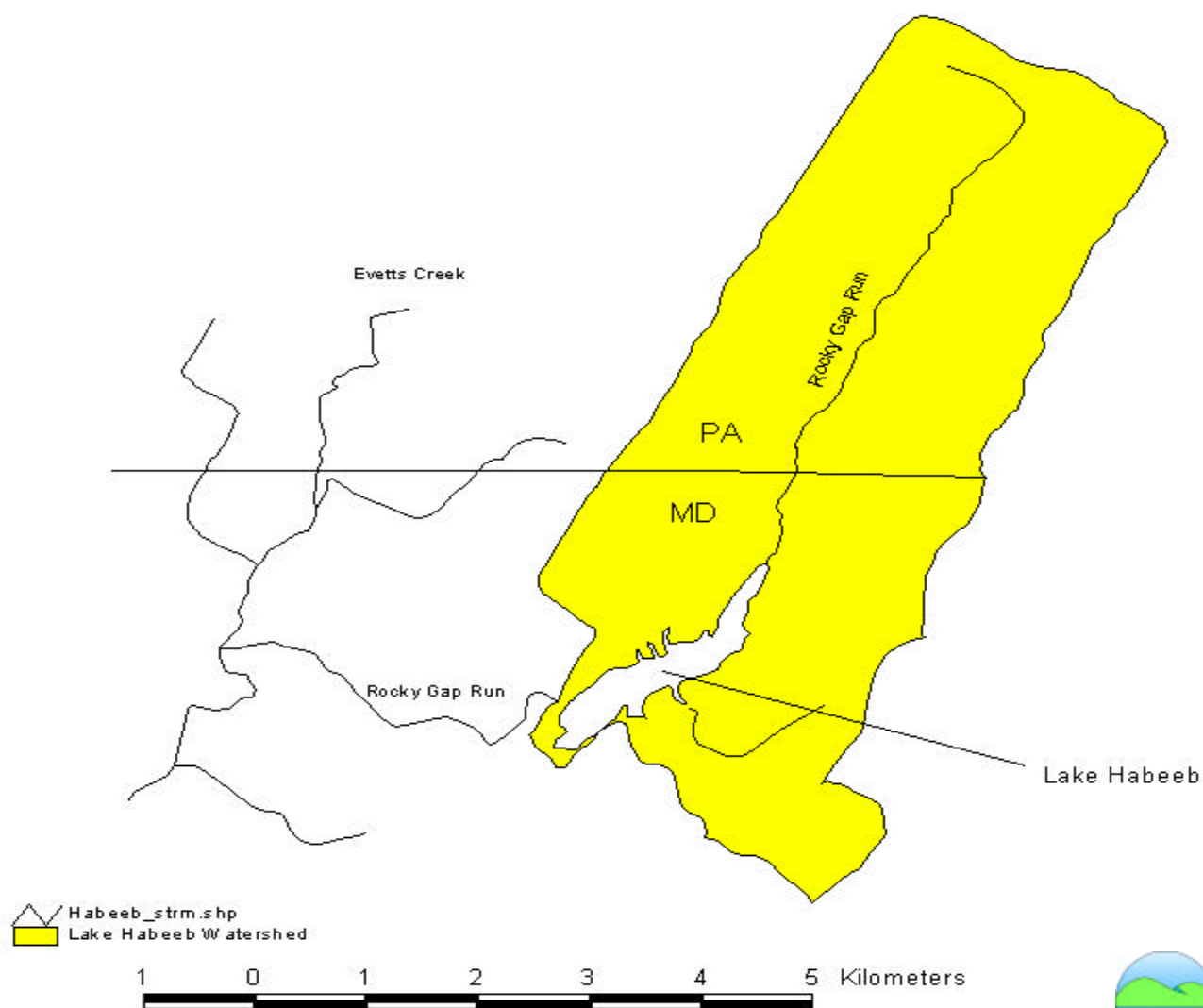
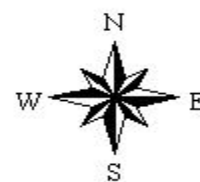
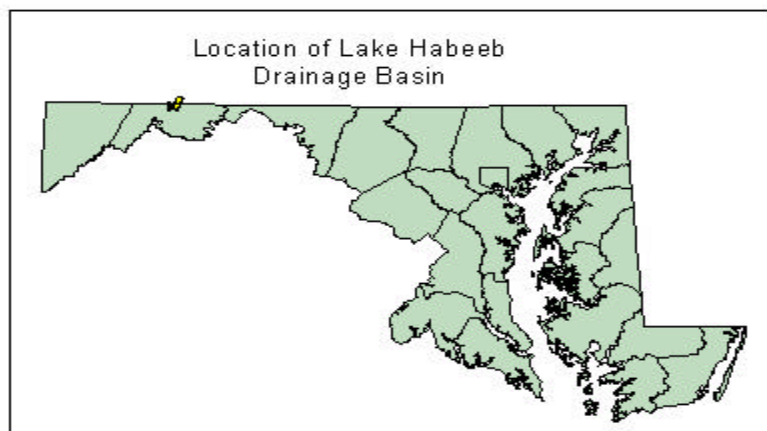
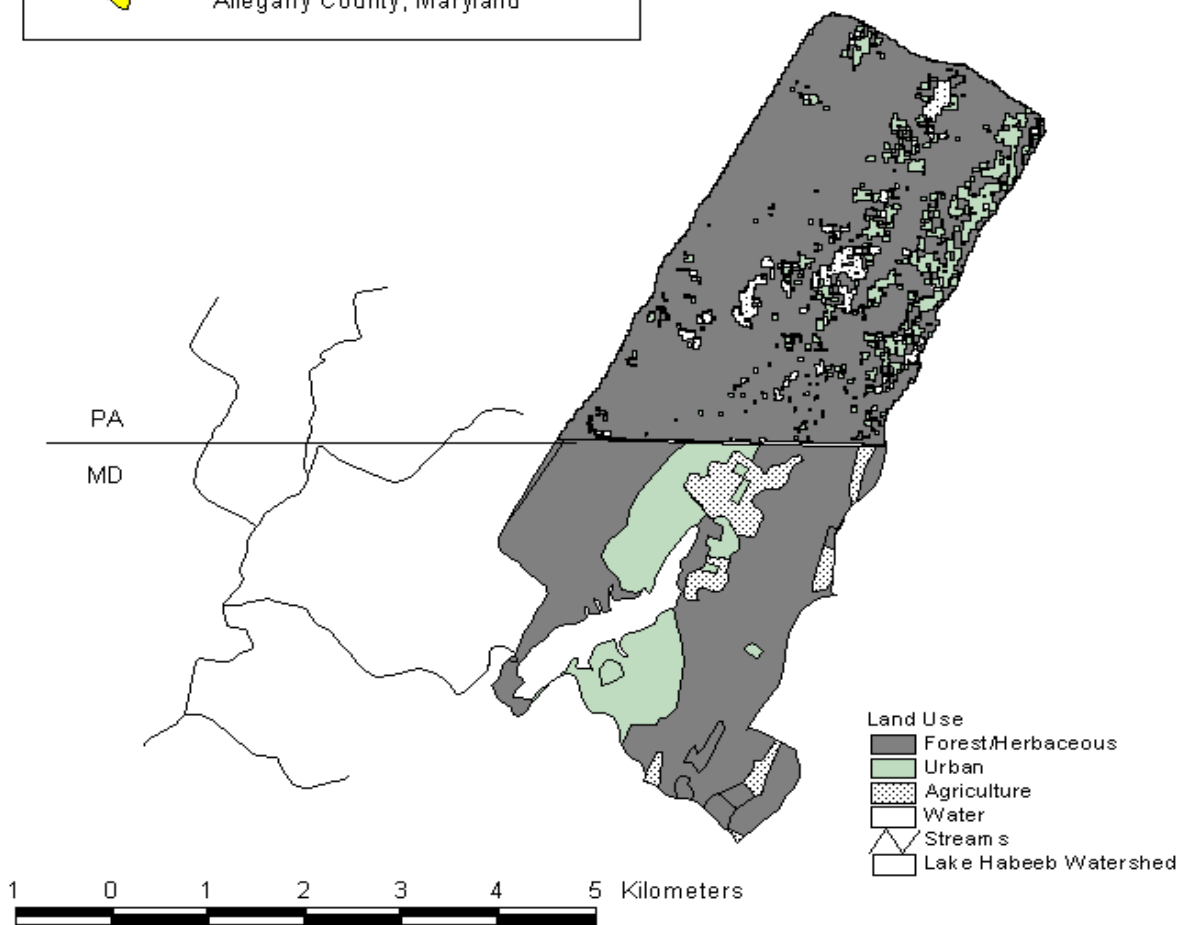
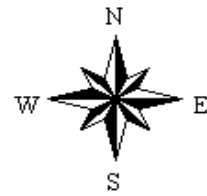
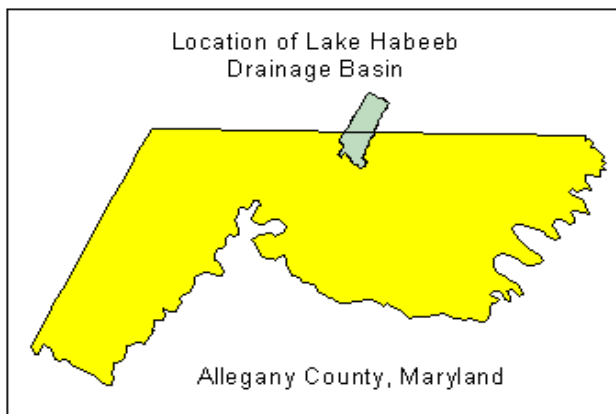


Figure 1 – Location Map of Lake Habeeb in Allegany County, Maryland

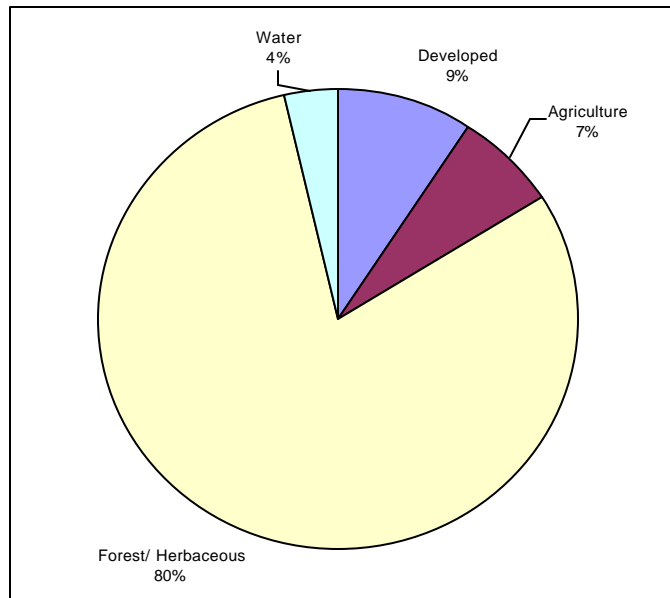


Sources:  
Land Use for Maryland: Maryland Office of Planning, 1997.  
Land Use for Pennsylvania: MRLC 1994



Figure 2 – Predominant Land Use In Lake Habeeb Watershed





**Figure 3. Land Use in Drainage Basin of Lake Habeeb**

## **2.2 Water Quality Characterization**

Lake Habeeb was identified as oligo-mesotrophic, with low dissolved oxygen levels, in the *Maryland Lake Water Assessment Report* (March 1998). As a result of this evaluation, Lake Habeeb was added to Maryland's 1998 303(d) list.

Lake Habeeb was monitored in July and September of 1993 (MDE Lake Water Quality Assessment Project, 1993). Water quality samples were collected once in each month. Samples were collected from one station near the spillway, and one station at mid-lake, off the water intake. Water samples were collected from a vertical profile of the water column. Samples were analyzed by the Maryland Department of Health and Mental Hygiene for total phosphorus, soluble orthophosphorus, nitrate and nitrite N, total Kjeldahl nitrogen, total organic solvents and chlorophyll *a*. Physical measurements of depths, water temperatures, pH, conductivity and dissolved oxygen were recorded in the field from the surface, middle and lower portion of the water column. A summary from the MDE Lake Water Quality Assessment Project follows. Detailed water quality data are presented in Appendix A.

Lake Habeeb has recently been monitored once a month by MDE, in March, April, May, June, and July 1999. Water quality samples were collected once in each month. Samples were collected in Rocky Gap Run from one station at the base of the dam and one station near the road leading to the campground. Samples were analyzed by the Maryland Department of Health and Mental Hygiene for total phosphorus, particulate carbon, total dissolved phosphorus, nitrite-

nitrate, nitrite, ammonia, total dissolved nitrogen, silica, orthophosphate, particulate nitrogen, dissolved organic compound, particulate phosphorus, and total suspended solids.

Observed chlorophyll *a* concentrations ranged from 1.0 to 3.4 µg/l during the 1993 sampling events, and from 0.2 to 5.4 µg/l during the 1999 sampling events.

Dissolved oxygen (DO) concentrations ranged from 0.1 to 11.3 mg/l along the vertical profile. Oxygen depletion occurs discontinuously, coincident with the depth at which thermal stratification was observed (i.e. about 8 m) during the two sampling events in 1993. Low DO conditions in the reservoir during the summer were observed by Department of Natural Resources (Inventory of Maryland Dams and Hydropower Resources, DNR 1985).

In 1993, total Kjeldahl nitrogen ranged from 0.17 to 0.23 mg/l in Lake Habeeb. Total phosphorus concentrations ranging from 0.01 mg/l to 0.039 mg/l slightly exceeded the range of 0.01 mg/l to 0.03 mg/l for lakes that do not exhibit signs of over-enrichment (Reid 1961).

During the 1999 sampling event, total dissolved phosphorus concentrations ranging from 0.001 mg/l to 0.026 mg/l were observed in Lake Habeeb. Particulate phosphorus concentrations in 1999 ranged from 0.001 mg/l to 0.032 mg/l. Total dissolved nitrogen ranged from 0.25 mg/l to 0.80 mg/l and particulate nitrogen ranged from 0.014 mg/l to 0.123 mg/l in Lake Habeeb.

Water temperatures taken during the 1993 summer sampling period ranged from 25.2°C to 26.6°C in the surface water depth (0.3-1 meter column); 23°C to 26.5°C in the 2-4 meter water column; 11.7°C to 24.5°C in the 5-7 meter water column; 7.8°C to 12.3°C in the 8-11 meter water column; and 6.9 to 8.6°C in the 12-18 meter water column. A similar range was observed again in 1999. This wide range of water temperatures, with an abrupt discontinuity at about 5 m, indicates that Lake Habeeb is thermally stratified and not well mixed.

## **2.3 Water Quality Impairment**

The Maryland water quality standards Surface Water Use Designation (COMAR 26.08.02.07) for Lake Habeeb is Use III-P – *Natural Trout Waters, and Public Water Supply*. The water quality impairments of Lake Habeeb consist of a violation of the numeric water quality for dissolved oxygen, and violations of general narrative criteria applicable to Use III-P waters. The substance causing these water quality violations is phosphorus (see the discussion of the nitrogen/phosphorus ratio, under Section 4.2 “Analysis Framework,” for an explanation of how phosphorus was determined to be the limiting nutrient associated with the eutrophication problems). Growth of the spiny naiad requires drawdown of the reservoir biennially during winter months (Inventory of Maryland Dams and Hydropower Resources, DNR 1985).

According to the numeric criteria for dissolved oxygen (DO), concentrations may not be less than 5.0 mg/l at any time, with a minimum daily average of not less than 6.0 mg/l (COMAR 26.08.02.03-3A(2)) unless resulting from naturally occurring conditions (COMAR 26.08.02.03.A(2)). In lake environments, low levels of dissolved oxygen are expected in bottom waters even under optimal natural conditions. However, achievement of the numeric criteria is expected in the well-mixed surface waters.

Lake Habeeb water temperatures indicate that the lake is thermally stratified and not well mixed. During the 1993 sampling period (July and September), DO concentrations as high as 8.1 mg/l were observed at the surface (0.3-4 meter depths) of Lake Habeeb, with DO values as low as 0.1 mg/l at a depth of 13-16 meter. Low DO levels in the summer are a common occurrence (Inventory of Maryland Dams and Hydropower Resources, DNR 1985).

### **3.0 TARGETED WATER QUALITY GOALS**

The overall objective of the TMDL established in this document is to reduce phosphorus loads to levels that are expected to result in meeting all water quality criteria that support the Use III-P designation. Specifically, one goal is to reduce the phosphorus load. This is predicted in turn to reduce excessive algae growth, which leads to violations of the numeric DO criteria and the violation of various narrative criteria associated with nuisances.

In summary, the TMDL for phosphorus is intended to:

1. Assure that minimum dissolved oxygen criteria are maintained both in the epilimnion and in the deeper waters of Lake Habeeb:
  - A minimum of 5.0 mg/l, and a minimum daily average of not less than 6.0 mg/l, in the surface layer (epilimnion);
  - A minimum DO saturation of 56% and associated temperature-dependent DO concentration below the epilimnion (see Appendix A); and
2. Resolve violations of narrative criteria associated with phosphorus enrichment of Lake Habeeb, to assure that algal production is consistent with the desired trophic status.

### **4.0 TOTAL MAXIMUM DAILY LOAD AND ALLOCATIONS**

#### **4.1 Overview**

This subsection describes how the nutrient TMDL and loading allocations were developed for Lake Habeeb. The second subsection describes the analysis for determining that phosphorus is likely to be the limiting nutrient in Lake Habeeb, and the methodological framework for estimating a permissible phosphorus load. The third subsection summarizes the analysis used to establish the maximum allowable phosphorus load. The fourth subsection provides a discussion of the analytical results. The fifth and sixth subsections describe the translation of these results into statements of a Total Maximum Daily Load and allocations. The seventh subsection describes the margin of safety. The last subsection summarizes the TMDL, and allocations to nonpoint sources and the margin of safety.

## 4.2 Analytical Framework

Lake Habeeb suffers from excessive nutrient enrichment. The TMDL for phosphorus is based on a widely accepted empirical method known as the Vollenweider Relationship. The relationship predicts the degree of a lake's trophic status as a function of the areal phosphorus loading. R. A. Vollenweider (1968) developed the relationship by assessing a large number of lakes. He established a linear relationship between the log of the phosphorus loading ( $L_p$ ) and the log of the ratio of the lake's mean depth ( $\bar{z}$ ) to hydraulic residence time ( $\tau_w$ ) (Figure 4). This method is advantageous for a number of reasons: It is based on observed data collected from a wide range of lakes; its application is conceptually simple and does not require the assumptions of many unknown parameters; and it is recognized by the scientific community as a reasonable method of predicting the trophic status of lakes.

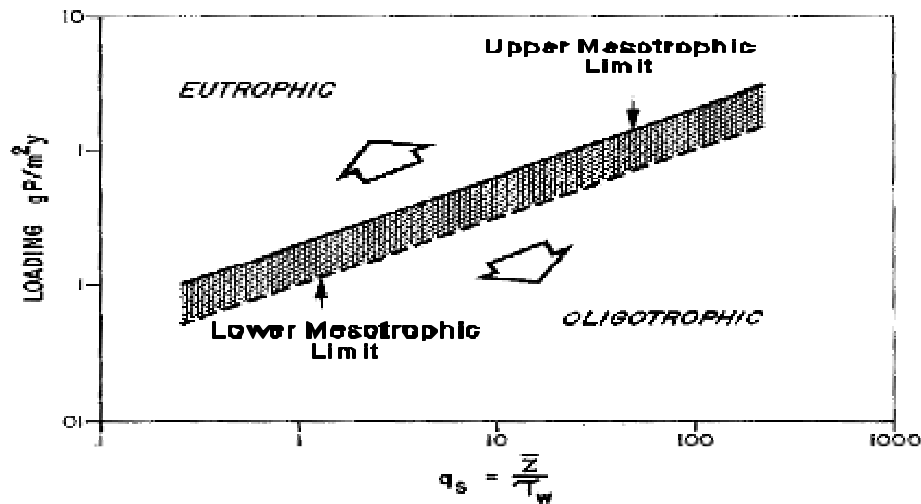


Figure 4. The Vollenweider Relationship

There are other, more complex approaches (i.e., water quality models that simulate eutrophication processes) that can also yield acceptable results. However, such methods require extensive data and the investment of substantial resources to develop. In light of the data available for this TMDL and the small size of the watershed, the Vollenweider Relationship constitutes a sufficient, readily available tool.

Nitrogen and phosphorus are essential nutrients for algae growth. However, common types of algae require different amounts of these two nutrients. If one nutrient is available in great abundance relative to the other nutrient, then the nutrient that is less available restricts the amount of plant matter that can be produced, regardless of the amount of the other nutrient that is available. This latter nutrient is called the “limiting nutrient.” Applying the Vollenweider Relationship necessitates that phosphorus be the limiting nutrient. Thus, before considering the

application of the Vollenweider Relationship, it is necessary to examine the ratio of nitrogen to phosphorus to establish whether phosphorus is the limiting nutrient.

In general, an N:P ratio in the range of 5:1 to 10:1 by mass is associated with plant growth being limited by neither phosphorus nor nitrogen. If the N:P ratio is greater than 10:1, phosphorus tends to be limiting, and if the N:P ratio is less than 5:1, nitrogen tends to be limiting (Chiandani et al., 1974). The average of the two concentrations, total nitrogen (calculated by adding the total dissolved nitrogen and particulate nitrogen) and total phosphorus (calculated by adding the total dissolved phosphorus and particulate phosphorus), of the March, April, May, June, and July 1999 sampling events were used to calculate the N:P ratio. A N:P ratio of 19:1 was computed, which supports the use of the Vollenweider Relationship. A ratio was also calculated using the average concentrations of total dissolved nitrogen and total dissolved phosphorus of the March, April, May, June, and July 1999 sampling events. A N:P ratio of 62:1 was computed, which also supports the use of the Vollenweider Relationship. Supporting data are provided in Appendix A.

### 4.3 Vollenweider Relationship Analysis

The Vollenweider Relationship establishes a linear relationship between the log of the phosphorus loading ( $L_p$ ) and the log of the ratio of the lake's mean depth ( $\bar{z}$ ) to hydraulic residence time ( $\tau_w$ ). Thus, the Vollenweider Relationship requires the computation of three key values: (1) the average annual phosphorus loading ( $L_p$ ), (2) the lake's mean depth ( $\bar{z}$ ), and (3) the hydraulic residence time ( $\tau_w$ ). The computations and results of the Vollenweider Relationship are summarized below. See Appendix A for details of the computations and supporting data.

#### Lake Habeeb Mean Depth ( $\bar{z}$ ):

The application of the Vollenweider assumes the lake's physical dimensions when the lake and dam were constructed in 1969. The mean lake depth was calculated using lake volume and surface area given in the Inventory of Maryland Dams and Hydropower Resources (DNR 1985). The cited surface area and volume of Lake Habeeb are 208.5 acres (9,082,260 ft<sup>2</sup>) and 5381 acre feet (234,396,360 ft<sup>3</sup>), respectively.

The mean depth was thus calculated as follows:

- ***Lake Habeeb Mean Depth ( $\bar{z}$ ):***  $(Volume)/(Surface\ Area) = 7.8\ m\ or\ 25.8\ ft$

#### Phosphorus Loading to Lake Habeeb ( $L_p$ ):

The current estimated total phosphorus loading is 1095 lbs/year (or 497,727 g/year) based on loading coefficients from the Chesapeake Bay Program, segment 160, Phase 4 Watershed Model. Expressing this value as a loading per surface area of the lake gives:

- ***Annual Phosphorus Load ( $L_p$ ) is:***  $0.6\ g/m^2\ yr$ . Details are provided in Appendix A.

### Lake Habeeb Hydraulic Residence Time ( $\tau_w$ )

Residence time ( $t_w$ ) is computed by dividing the lake volume by annual discharge. For Lake Habeeb, average discharge data are unavailable. Since discharge data are unavailable, this parameter was estimated by examining a number of watersheds of various sizes on the North Potomac Branch Basin for which long-term flow data were readily available from the U.S. Geological Survey. Average daily flow from each of these stations was plotted against watershed area. Linear regression was used to estimate the average annual flow. Flow from Lake Habeeb is estimated as follows (details are shown in Appendix A):

- **Flow (Q) = watershed area (8.8 mi<sup>2</sup>) x 1.356 = 11.93 cfs = 8,643 acre feet/year**

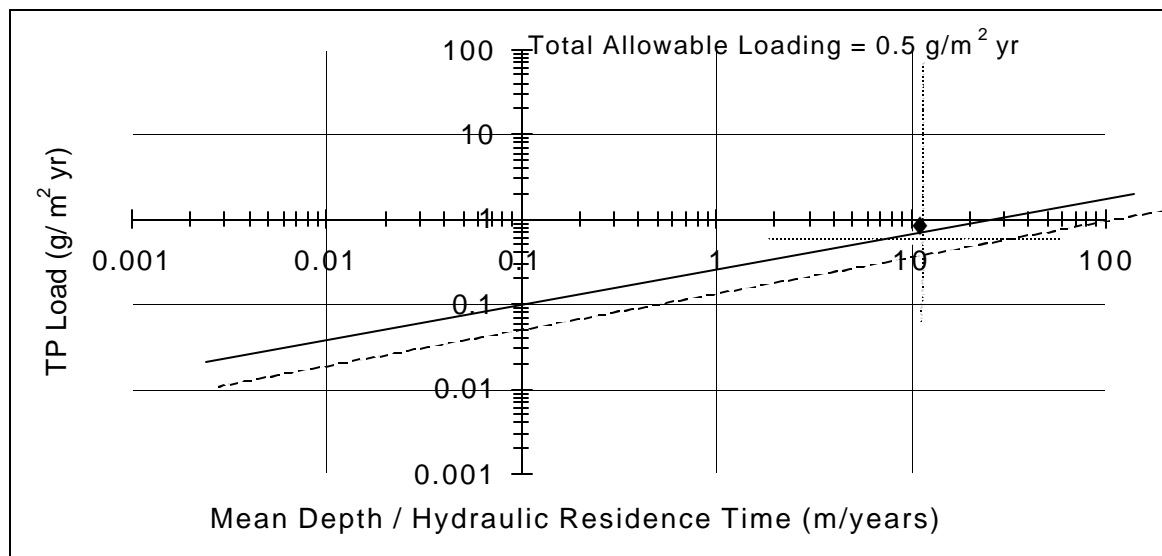
The hydraulic residence time is computed as volume/outflow; the time it would take to drain the lake. Assuming a volume of 5,381 acre feet (DNR, 1985), from above, and a discharge rate of 8,643 acre per year (DNR, 1985) the hydraulic residence time is calculated as follows:

- **5,381 acre feet ÷ 8,643 acre feet/year = 0.62 years**
- ***Lake Habeeb Hydraulic Residence Time ( $t_w$ ): 0.62 years = 226 days***

The mean depth of the lake (7.9 m) is then divided by hydraulic residence time (0.62 years) to yield  $q_s$ , the parameter with which to compare phosphorus loading using the Vollenweider Relationship to assess the lake's trophic status. For Lake Habeeb,  **$q_s = 12.58 \text{ m/yr}$** .

### **4.4 Vollenweider Relationship Results**

The basic elements of the Vollenweider Relationship, established above, were combined to estimate both the current trophic status of Lake Habeeb, and the maximum allowable unit loading. The current estimated loading rate of 0.6 g/m<sup>2</sup> yr would suggest a current trophic status slightly within the mesotrophic range, as indicated on Figure 5 by a diamond “♦”. Lake Habeeb is classified as oligo-mesotrophic (DNR 1998). The maximum allowable unit loading of 0.5 g/m<sup>2</sup> yr for a lake with mean depth of 7.9 m and hydraulic residence time of 0.62 years is indicated by the intersection of the cross-hairs (See Appendix A). The TMDL implications are presented below in Section 4.5.



**Figure 5. Vollenweider Results for Lake Habeeb**

#### **4.5 Total Maximum Daily Load**

This TMDL considers seasonal variations by estimating loading rates over the entire year. This captures the dry weather loading rates, which generally occur during the warmer months when algae production is most prevalent. It also captures the wet-weather loading rates, which contribute significant sediment-bound sources of phosphorus. The Vollenweider Relationship specifically uses long-term loading estimates to avoid adopting a single transient loading pulse, which would yield erroneous results. The critical conditions are accounted for implicitly in the empirical Vollenweider Relationship. The resultant TMDL for phosphorus is based on the unit allowable loading indicated by the results of the Vollenweider Relationship. That is, the unit loading per square meter ( $0.5 \text{ g/m}^2 \text{ year}$ ) times the total surface area of the lake ( $844,076 \text{ m}^2$ ) or  $422,038 \text{ g/yr}$ . This represents a 24% reduction in phosphorus loading.

The link between DO concentration and the lake's trophic status (as defined by the Vollenweider Relationship) is indirect, but may be inferred as described below. Nutrient overenrichment causes excess algal blooms, which eventually die off and decompose, consuming DO.

The DO in the surface layer of Lake Habeeb is currently within State standards (see Table A-1, Appendix A). An assessment is made of the processes that determine DO concentration in the sub-epilimnetic portion of the lake (see Appendix A). The assessment is based on critical conditions and uses conservative assumptions. These processes, as they apply to Lake Habeeb, are outlined below:

- Dissolved oxygen saturation capacity as a function of water temperature.
- Sediment Oxygen Demand (SOD).
- Carbonaceous Biochemical Oxygen Demand (CBOD).

According to calculations presented in Appendix A, it is expected that an areal phosphorus load of 0.5 g/m<sup>2</sup> will result in hypolimnetic DO concentrations of about 4.8-6.9 mg/l.

**PHOSPHORUS TMDL      422,038 g/yr = 929 lb/yr**

#### **4.6 TMDL Allocation**

The watershed that drains to Lake Habeeb contains no permitted point source discharges. Hence, the entire allocation will be made to nonpoint sources. The model uses Chesapeake Bay Program, Phase 4 Phosphorus loading coefficients to estimate the loading rates, which represent the cumulative impact from all sources—naturally-occurring and human-induced. Details are described in the technical memorandum entitled “Significant Phosphorus Nonpoint Sources in the Lake Habeeb Watershed”.

#### **4.7 Margin of Safety**

A margin of safety (MOS) is required as part of a TMDL in recognition of the fact that there are many uncertainties in scientific and technical understanding of water quality in natural systems. Specifically, knowledge is incomplete regarding the exact nature and magnitude of pollutant loads from various sources and the specific impacts of those pollutants on the chemical and biological quality of complex, natural water bodies. The MOS is intended to account for such uncertainties in a manner that is conservative from the standpoint of environmental protection.

Based on EPA guidance, the MOS can be achieved through one of two approaches (EPA, April 1991). One approach is to reserve a portion of the loading capacity as a separate term in the TMDL (i.e., TMDL = WLA + LA + MOS). The second approach is to incorporate the MOS as part of the design conditions for the WLA and the LA computations.

Maryland has elected to incorporate an explicit margin of safety for this phosphorus TMDL. Following the first approach, the load allocated to the MOS was computed as 10% of the total allowable load. This value is considered reasonable in that it implies an additional 10% reduction in nonpoint source phosphorus loading beyond what would be expected to meet the goal.

#### **4.8 Summary of Total Maximum Daily Load**

The annual TMDL for Phosphorus (*lb/yr*):

<b>TMDL</b>	<b>=</b>	<b>WLA</b>	<b>+</b>	<b>LA</b>	<b>+</b>	<b>MOS</b>
<b>929</b>	<b>=</b>	<b>0</b>	<b>+</b>	<b>836</b>	<b>+</b>	<b>93</b>

On average, this TMDL represents a daily phosphorus load of 2.5 lbs/day.

Where:      WLA = Point Source  
               LA = Nonpoint Source  
               MOS = Margin of Safety



## **5.0 ASSURANCE OF IMPLEMENTATION**

Lake Habeeb is located in a watershed in which the impairment is driven entirely by nonpoint source contributions. As such, the implementation provisions will need to be more rigorous and iterative. Significant phosphorus reductions are required to meet the load allocation of this TMDL. The certainty of implementation of the phosphorus reduction plan in this watershed will be enhanced by three specific programs: the Water Quality Improvement Act of 1998 (WQIA), and the EPA-sponsored Clean Water Action Plan of 1998 (CWAP).

Maryland's WQIA requires that comprehensive and enforceable nutrient management plans be developed, approved and implemented for all agricultural lands throughout Maryland. This act specifically requires that these phosphorus nutrient management plans be developed and implemented by 2004. Thus, a specific milestone and benchmark, including a final expected attainment date have been established for this TMDL against which the adequacy of the initial load allocation and implementation plan can be measured. The water quality response accomplished by the date of this benchmark can be the basis for triggering appropriate load allocation revisions (either higher or lower). Additionally, as part of Maryland's Watershed Cycling Strategy, follow-up monitoring and assessments will be conducted to (1) determine the effect of the practices on water quality and related conditions, (2) determine the degree to which the selected practices are implemented, and (3) to the extent possible, determine the efficacy and impacts of the practices chosen. Based on this monitoring and assessment program, the TMDL will be evaluated as to whether additional practices must be employed in order to eliminate any remaining impairment.

Maryland's CWAP has been developed in a coordinated manner with the State's 303(d) process. All Category I watersheds identified in Maryland's Unified Watershed Assessment process are totally coincident with the impaired waters list for 1996 and 1998 approved by EPA. The State has given a high priority for funding assessment and restoration activities to these watersheds.

Maryland's Tributary Strategies have already established a voluntary program and an institutional framework in which to advance the goals of this TMDL. The findings of the TMDL analysis indicate that the implementation of the TMDL on the basis of external loading controls would require a 24% reduction of external phosphorus loadings.

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## **Appendix A**

### **Lake Habeeb Water Quality**

Water quality data from Lake Habeeb were collected in 1993 (DNR, Trophic Lake Assessment Study) and 1999 (MDE, Lake Water Quality Assessment Project). A summary of the water quality data was provided in the main body of this report. Tables A1 through A4 provide the underlying data from which the summaries were derived.

### **Assessment of the N:P Ratio for Lake Habeeb**

Before considering the application of the Vollenweider Relationship, it is necessary to examine the ratio of nitrogen (N) to phosphorus (P) to establish whether phosphorus is the limiting nutrient. In general, an N:P ratio in the range of 5:1 by mass is associated with plant growth being limited by neither phosphorus nor nitrogen. If the N:P ratio is greater than 10, phosphorus tends to be limiting, and if the N:P ratio is less than 5, nitrogen tends to be limiting (Chiandani, et al., 1974).

The N:P ratio was calculated using data from the two sampling events (MDE Lake Water Quality Assessment Project). The average of the two concentrations, total nitrogen (calculated by adding the total dissolved nitrogen and particulate nitrogen) and total phosphorus (calculated by adding the total dissolved phosphorus and particulate phosphorus), of the March, April, May, June, and July 1999 sampling events were used to calculate the N:P ratio. A N:P ratio of 19:1 was computed which supports the use of the Vollenweider Relationship. A N:P ratio of 62:1 was also calculated using the average concentrations of total dissolved nitrogen and total dissolved phosphorus of the March, April, May, June, and July 1999 sampling events. This also supports the use of the Vollenweider Relationship.

**Table A1**  
**Field Data For Lake Habeeb – 1993**  
**Water Column Results**

STATION	DATE	TIME	DEPTH (m)	WATER TEMP (°C)	PH FIELD	DO (mg/l)	COND (mg/l)
RKG0025	7/19/93	1130	0.3	26.6	7.9	7.9	97
RKG0025	7/19/93	1130	1.0	26.6	7.8	7.9	96
RKG0025	7/19/93	1130	2.0	26.5	7.6	7.9	96
RKG0025	7/19/93	1130	3.0	25.7	7.5	8.2	96
RKG0025	7/19/93	1130	4.0	23	7.1	10.5	92
RKG0025	7/19/93	1130	5.0	19.4	6.8	10.4	90
RKG0025	7/19/93	1130	6.0	14.4	6.7	9.5	90
RKG0025	7/19/93	1130	7.0	11.7	6.7	7.4	92
RKG0025	7/19/93	1130	8.0	9.4	6.6	5.2	94
RKG0025	7/19/93	1130	9.0	8.5	6.6	3.7	96
RKG0025	7/19/93	1130	10.0	8.0	6.6	3.1	99
RKG0025	7/19/93	1130	11.0	7.8	6.6	3.3	98
RKG0025	7/19/93	1130	12.0	7.6	6.6	2.3	99
RKG0025	7/19/93	1130	13.0	7.3	6.7	2.4	98
RKG0025	7/19/93	1130	14.0	7.3	6.7	2.4	98
RKG0025	7/19/93	1130	15.0	7.1	6.7	1.0	100
RKG0025	7/19/93	1130	16.0	7.0	6.7	0.1	102
RKG0025	7/19/93	1130	17.0	7.0	6.6	0.1	103
RKG0025	7/19/93	1130	18.0	6.9	6.7	0.1	108
RKG0025	7/19/93	1130	18.7	6.8	6.7	0.1	108
RKG0034	7/19/93	1225	0.3	26.4	8.0	7.7	94
RKG0034	7/19/93	1225	1.0	26.4	7.9	7.7	94
RKG0034	7/19/93	1225	2.0	26.4	7.7	7.8	94
RKG0034	7/19/93	1225	3.0	26.3	7.5	7.7	93
RKG0034	7/19/93	1225	4.0	24.6	7.0	6.2	93
RKG0034	7/19/93	1225	5.0	19.0	7.1	6.3	91
RKG0034	7/19/93	1225	6.0	14.0	7.3	4.3	94
RKG0034	7/19/93	1225	6.7	12.6	7.5	4.1	96
RKG0025	9/7/93	1350	0.3	25.5	8.0	8.1	99
RKG0025	9/7/93	1350	1.0	25.2	8.0	8.1	100
RKG0025	9/7/93	1350	2.0	25.0	8.0	8.1	100
RKG0025	9/7/93	1350	3.0	24.9	7.9	8.1	100
RKG0025	9/7/93	1350	4.0	24.8	7.9	8.1	99
RKG0025	9/7/93	1350	5.0	24.5	7.7	8.0	98
RKG0025	9/7/93	1350	6.0	20.8	7.3	11.3	93
RKG0025	9/7/93	1350	7.0	16.3	6.5	4.5	94
RKG0025	9/7/93	1350	8.0	12.3	6.5	3.0	95
RKG0025	9/7/93	1350	9.0	10.0	6.5	1.3	97
RKG0025	9/7/93	1350	10.0	9.4	6.5	1.3	98
RKG0025	9/7/93	1350	11.0	8.7	6.5	1.0	99
RKG0025	9/7/93	1350	12.0	8.6	6.5	0.5	100
RKG0025	9/7/93	1350	13.0	8.3	6.6	0.1	102
RKG0025	9/7/93	1350	14.0	8.1	6.6	0.1	102
RKG0025	9/7/93	1350	15.0	8.0	6.7	0.1	103
RKG0025	9/7/93	1350	16.0	7.8	6.8	0.1	110
RKG0025	9/7/93	1350	17.0	7.7	6.7	0.1	115
RKG0025	9/7/93	1350	18.0	7.7	6.8	0.1	116
RKG0025	9/7/93	1350	19.2	7.8	6.8	0.1	119
RKG0034	9/7/93	1445	0.3	26.0	8.0	8.0	98
RKG0034	9/7/93	1445	1.0	25.7	8.0	8.0	99
RKG0034	9/7/93	1445	2.0	25.4	7.9	8.0	99
RKG0034	9/7/93	1445	3.0	25.3	7.7	7.9	97
RKG0034	9/7/93	1445	4.0	25.1	7.5	7.8	98
RKG0034	9/7/93	1445	5.0	23.9	7.1	7.8	96
RKG0034	9/7/93	1445	6.0	20.3	6.8	7.0	92
RKG0034	9/7/93	1445	7.0	14.2	6.6	0.7	99
RKG0034	9/7/93	1445	8.2	11.5	6.7	0.1	101

**Table A2**  
**Lake Habeeb Nutrient Data (1993)**

STATION	DATE	TIME	DEPTH	TOC	TKN	TP
			(m)	(mg/l)	(mg/l)	(mg/l)
RKG0025	7/19/93	1130	0.3	N/A	0.19	0.032
RKG0025	7/19/93	1130	0.3	N/A	0.23	0.039
RKG0034	7/19/93	1225	0.3	N/A	0.17	0.037
RKG0025	9/17/93	1350	0.3	3.96	0.22	0.01
RKG0034	9/17/93	1445	0.3	3.86	0.19	0.01

N/A = No sample.

**Table A3**  
**Lake Habeeb Chlorophyll Data (1993)**

STATION	DATE	TIME	DEPTH	CHLA	PHEA
			(m)	(µg/l)	(mg/l)
RKG0025	7/19/93	1130	0.0	2.4	0.0
RKG0025	7/19/93	1130	0.3	1.2	0.2
RKG0025 (dup)	7/19/93	1130	0.3	1.3	-0.1
RKG0034	7/19/93	1225	0.0	1.5	0.0
RKG0034	7/19/93	1225	0.3	1.7	0.2
RKG0025	9/21/93	1350	0.0	3.4	0.9
RKG0025	9/21/93	1350	0.3	1.0	0.3
RKG0034	9/21/93	1445	0.0	2.3	0.1
RKG0034	9/21/93	1445	0.3	1.7	-0.1

**Table A4**  
**Lake Habeeb Surface Water Quality Data (MDE 1999<sup>1</sup>)**

Station	Date	PC (mg/l)	TDP (mg/l)	NO <sub>23</sub> (mg/l)	NO <sub>2</sub> (mg/l)	NH <sub>4</sub> (mg/l)	TDN (mg/l)	Si (mg/l)	PO <sub>4</sub> (mg/l)	PN (mg/l)	DOC (mg/l)	PP (mg/l)	TSS (mg/l)
RKG0023	Mar 30, 1999	0.415	0.004	0.126	0.001	0.015	0.480	0.800	0.0018	0.055	3.420	0.002	2.400
RKG0041	Mar 30, 1999	0.176	0.003	0.129	0.001	0.004	0.310	2.250	0.0011	0.017	2.750	0.001	2.400
RKG0023	Apr 15, 1999	0.435	0.001	1.123	0.002	0.041	0.400	0.780	0.001	0.055	3.040	0.003	2.400
RKG0041	Apr 15, 1999	0.344	0.001	0.108	0.002	0.022	0.250	2.290	0.002	0.123	2.870	0.001	2.400
RKG0023	May 19, 1999	0.508	0.026	0.247	0.002	0.129	0.530	0.990	0.021	0.054	3.280	0.008	2.400
RKG0041	May 19, 1999	0.274	0.002	0.136	0.0007	0.003	0.290	2.320	0.001	0.034	2.670	0.003	2.700
RKG0023	Jun 2, 1999	0.344	0.023	0.132	0.0036	0.227	0.530	1.290	0.0044	0.049	3.430	0.005	2.400
RKG0041	Jun 2, 1999	0.221	0.003	0.524	0.0067	0.108	0.800	2.170	0.0036	0.031	4.340	0.003	2.400
RKG0023	July 13, 1999	0.865	0.003	0.118	0.0027	0.361	0.730	1.290	0.0033	0.086	3.260	0.032	8.500
RKG0041	July 13, 1999	0.092	0.001	0.225	0.0011	0.012	0.430	1.350	0.0006	0.014	1.900	0.001	2.400

<sup>1</sup>All samples were collected at the surface.

DOC = Dissolved Organic Carbon

NO<sub>23</sub> = Nitrite Nitrate

NO<sub>2</sub> = Nitrite

NH<sub>4</sub> = Ammonia

PC = Particulate Carbon

PO<sub>4</sub> = Orthophosphate

PN = Particulate Nitrogen

PP = Particulate Phosphorus

Si = Silica

TDN = Total Dissolved Nitrogen

TDP = Total Dissolved Phosphorus

TSS = Total Suspended Solids

**Table A5**  
**Water Quality (Chlorophyll) Data Lake Habeeb - 1999**

STATION	DATE	TIME	DEPTH (m)	CHLA (mg/l)
RKG0023	3/29/99	1300	0.0	5.4
RKG0041	3/29/99	1340	0.0	0.9
RKG0023	4/15/99	1310	0.0	3.3
RKG0041	4/15/99	1210	0.0	0.2

**Table A6**  
**Field Data For Lake Habib – 1999**  
**Water Column Results**

STATION	DATE	TIME	DEPTH (m)	WATER TEMP (°C)	PH FIELD	DO (mg/l)	COND (μohms/cm)
RKG0023	3/29/99	1340	0.0	6.5	6.6	12.8	60
RKG0041	3/29/99	1300	0.0	12.5	6.5	10.8	50
RKG0023	4/15/99	1245	0.0	6.7	6.4	11.8	55
RKG0041	4/15/99	1210	0.0	8.4	6.1	11.0	35
RKG0023	5/19/99	1350	0.0	11.0	6.4	9.5	65
RKG0041	5/19/99	1315	0.0	17.0	7.0	8.4	70
RKG0023	6/02/99	1455	0.0	11.9	6.2	8.4	70
RKG0041	6/02/99	1420	0.0	22.8	7.2	8.1	150
RKG0023	7/13/99	1500	0.0	13.9	6.6	8.6	126
RKG0041	7/13/99	1410	0.0	22.8	--	9.0	208
RKG0023	8/31/99	1505	0.0	9.2	7.1	7.62	47
RKG0025	8/31/99	1040	0.0	23.3	8.15	8.04	103
RKG0025	8/31/99	1040	1.0	23.3	8.15	8.09	103
RKG0025	8/31/99	1040	2.0	23.3	8.14	7.99	103
RKG0025	8/31/99	1040	3.0	23.3	8.14	8.04	104
RKG0025	8/31/99	1040	4.0	23.1	8.16	8.11	104
RKG0025	8/31/99	1040	5.0	23.1	8.09	7.97	103
RKG0025	8/31/99	1040	6.0	22.4	7.73	7.77	101
RKG0025	8/31/99	1040	7.0	17.3	6.97	7.44	99
RKG0025	8/31/99	1040	8.0	13.7	6.75	5.61	102
RKG0025	8/31/99	1040	9.0	11.8	6.67	4.32	104
RKG0025	8/31/99	1040	10.0	10.5	6.61	3.29	105
RKG0025	8/31/99	1040	11.0	9.7	6.58	2.42	106
RKG0025	8/31/99	1040	12.0	9.1	6.57	1.87	108
RKG0025	8/31/99	1040	13.0	8.8	6.53	0.96	110
RKG0025	8/31/99	1040	14.0	8.5	6.53	0.34	112
RKG0025	8/31/99	1040	15.0	7.8	6.61	0.34	115
RKG0025	8/31/99	1040	16.0	7.9	6.66	0.34	119
RKG0025	8/31/99	1040	17.0	7.9	6.68	0.35	123
RKG0025	8/31/99	1040	17.8	8.1	6.67	0.49	125
RKG0034	8/31/99	1305	0.0	23.3	7.98	7.91	103
RKG0034	8/31/99	1305	1.0	23.3	8.0	7.81	104
RKG0034	8/31/99	1305	2.0	23.2	8.01	7.91	104
RKG0034	8/31/99	1305	3.0	23.0	8.0	7.95	104
RKG0034	8/31/99	1305	3.5	22.9	7.98	7.89	104
RKG0034	8/31/99	1305	4.0	22.9	7.94	7.91	104
RKG0034	8/31/99	1305	5.0	22.7	7.87	7.8	104
RKG0034	8/31/99	1305	5.5	22.5	7.7	7.7	104
RKG0034	8/31/99	1305	6.0	22.3	7.73	7.67	104
RKG0034	8/31/99	1305	6.5	20.3	7.04	6.73	104
RKG0034	8/31/99	1305	7.0	17.9	6.8	5.96	101
RKG0034	8/31/99	1305	7.5	16.1	6.76	3.2	105
RKG0041	8/31/99	1305	0.0	18.1	7.8	8.83	72



## Supporting Calculations for the Vollenweider Analysis

### Lake Habeeb Mean Depth ( $\bar{z}$ ):

The mean lake depth was calculated using lake volume and surface area given in the Inventory of Maryland Dams and Hydropower Resources (DNR 1985). The cited surface area and volume of Lake Habeeb are 208.5 acres (9,082,260 ft<sup>2</sup>) and 5381 acre feet (234,396,360 ft<sup>3</sup>), respectively.

$$\text{Convert feet}^2 \text{ to m}^2 : \quad 9,082,260 \text{ ft}^2 \times 0.092 \text{ m}^2/\text{ft}^2 = 844,076 \text{ m}^2$$

$$\text{Convert acre feet to m}^3 : \quad 5381 \text{ acre feet} \times 1,233.5 \text{ m}^3/\text{acre feet} = 6,637,463 \text{ m}^3$$

The mean depth of Lake Habeeb is (Volume)/(Surface Area) is computed as:

$$6,637,463 \text{ m}^3 \div 844,076 \text{ m}^2 = \mathbf{7.9 \text{ m or } 25.8 \text{ ft}}$$

### Current Phosphorus Loading to Lake Habeeb (L<sub>p</sub>):

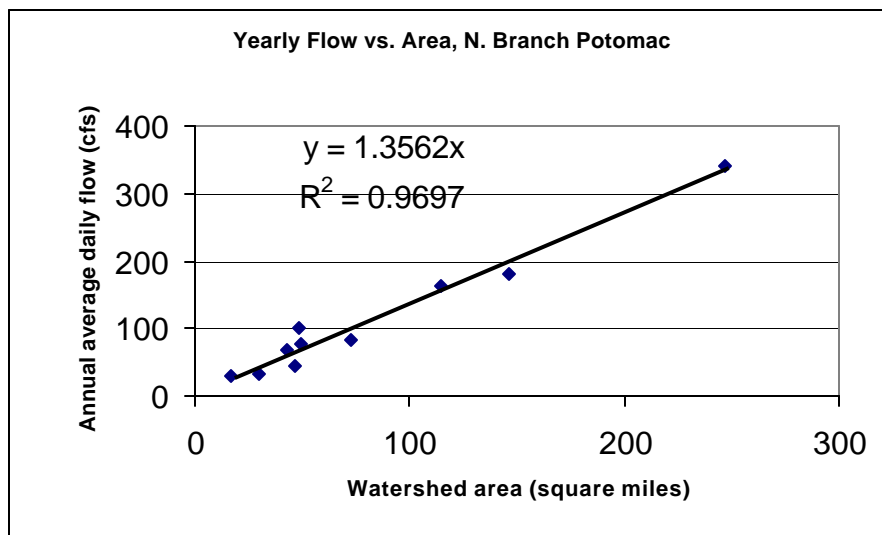
The total phosphorus loading from land is cited as 1095 lbs/year (497,727 g/yr) based on loading rates from the Chesapeake Bay Program Phase 4 Model, segment 160.

Using the estimated 1969 lake surface area (844,076 m<sup>2</sup>), this value can be converted to grams per square meter per year as follows:  $497,727 \text{ g/yr} \div 844,076 \text{ m}^2 = \mathbf{0.6 \text{ g/m}^2 \text{ yr}}$ .

### Lake Habeeb Hydraulic Residence Time ( $\tau_w$ ):

The hydraulic residence time is computed as volume/outflow; it is the time it would take to drain the lake.

Hydraulic residence time is calculated based on the lake volume and discharge rate. Since discharge data are unavailable, discharge was estimated by regressing watershed size versus all discharge data on record for ten watersheds of varying size in the North Branch of the Potomac Basin of Maryland. Linear regression provided a correlation coefficient ( $R^2$ ) of 0.9702 when the Y-intercept was not forced to zero, and 0.9697 when the Y-intercept was forced to zero. The high  $R^2$  shows a very strong positive correlation between area and resulting flow for a given watershed in the North Branch of the Potomac Basin. The insignificant change when the Y-intercept was forced to zero suggests that flow is not significantly affected by sources not proportional to direct runoff—for example, a spring-fed stream. This strengthens the case for estimating discharge of the lake as a function of watershed area. The regression line and equation are shown in Figure A-1 below. The overall Lake Habeeb watershed measures 8.8 mi<sup>2</sup>; the estimated discharge is thus 11.93 cfs (8,643 acre feet per year).



**Figure A-1. Discharge as function of watershed area, North Branch Potomac of Maryland**

Hydraulic residence time ( $\tau_w$ ) is calculated as follows:

$$(5381 \text{ acre feet}) \div (23.6 \text{ acre feet per day}) = 228 \text{ days.}$$

$$228 \text{ days} \div 365 \text{ days/yr} = \mathbf{0.62 \text{ yr}}$$

#### Ratio of Mean Depth to Hydraulic Residence Time ( $\bar{z}/\tau_w$ )

From the computations above the mean depth of Lake Habeeb ( $\bar{z}$ ) is 7.9 m, and the hydraulic residence time ( $\tau_w$ ) is 0.62 yr. The ratio was computed as:

$$7.9 \text{ m} / 0.62 \text{ yr} = \mathbf{12.74 \text{ m/yr}}$$

#### Graphing of Trophic Status of Lake Habeeb using the Vollenweider Relationship

The intersection of the phosphorus loading rate ( $L_p$ ) = 1.4 g/m<sup>2</sup>yr and the ratio ( $\bar{z}/\tau_w$ ) = 23.8 m/yr was plotted on log log paper to establish the trophic status of Lake Habeeb (See Figure 5).

#### Determination of the Oligo-mesotrophic Zone of Vollenweider's Diagram

Vollenweider's diagram categorizes lakes into three trophic states (eutrophic, mesotrophic, and oligotrophic) on the basis of the log-log relationship between areal P loading and  $q_s$ . Maryland's current methods categorize lakes into two additional trophic states—meso-eutrophic and oligo-mesotrophic. It was thus necessary to subdivide the mesotrophic portion of Vollenweider's diagram.

The oligo-mesotrophic range is the lower one-third of the mesotrophic portion of the Vollenweider's diagram.

For Lake Habeeb, the mesotrophic range of areal P loading was first estimated as per Vollenweider's methods. This "combined mesotrophic" range was then divided into three equal ranges to allow setting upper P loading limits for oligo-mesotrophic, mesotrophic, and meso-eutrophic lakes.

The combined mesotrophic portion of Vollenweider's diagram (i.e., before subdivision), for a lake with a  $q_s$  of 12.73 m/yr, ranges from 0.35 to 0.8 g/m<sup>2</sup>/yr. Each subdivision of this combined mesotrophic range is assigned its own range spanning 0.15 g/m<sup>2</sup>/yr. Thus, the oligo-mesotrophic range for Lake Habeeb lies within 0.35 – 0.50 g/m<sup>2</sup>/yr. The phosphorus TMDL is set at 0.50 g/m<sup>2</sup>/yr.

## Supporting Calculations for the TMDL Analysis

### Graphing of Maximum Allowable Unit Phosphorus loading of Lake Habeeb using the Vollenweider Relationship

Figure 5 (p.11) shows how the maximum allowable unit phosphorus loading can be read off of the log log paper. Point A represents the maximum allowable load, which includes the load allocation and the margin of safety (0.5 g/m<sup>2</sup>yr).

### Computing the Phosphorus TMDL

The TMDL is computed from the maximum unit load read from Point A on Figure 5:

$$\begin{aligned} &(\text{Unit loading}) \times (\text{Lake Surface Area}) = \text{Annual Loading} \\ &(0.5 \text{ g/m}^2\text{yr}) \times (844,076 \text{ m}^2) = \mathbf{422,038 \text{ g/yr}} \end{aligned}$$

Converted to pounds per year:

$$(422,038 \text{ g/yr}) \times (0.0022 \text{ lb/g}) = \mathbf{929 \text{ lbs/yr}}$$

### Computing the Phosphorus Margin of Safety

The Margin of Safety is computed as 10% of the total allowable unit loading:

$$\begin{aligned} &0.10 \times (\text{Total allowable loading}) = \text{Annual Loading} \\ &(0.10) \times (422,038) = \mathbf{42,204 \text{ g/yr}} \end{aligned}$$

Converted to pounds per year:

$$42,204 \text{ g/yr} \times (0.0022 \text{ lb/g}) = \mathbf{93 \text{ lb/yr}}$$

### Computing the Percentage Phosphorus Reduction

The necessary reduction in phosphorus loads, as a percentage of the current estimated load was computed as follows:

$$\frac{(\text{current load}) - (\text{allowable load}^*)}{(\text{current load})} =$$

$$\frac{(497,727 \text{ g/yr}) - (379,834 \text{ g/yr})}{(497,727 \text{ g/yr})} = 24\% \text{ reduction}$$

\* The allowable load does not include the margin of safety.

## Supporting Determination of the Expected Minimum DO below Epilimnion

As noted in the main body of this document, DO concentration in the surface waters currently meets State standards. The following analysis provides a linkage between the maximum allowable phosphorus load, as specified by the Vollenweider Relationship, and the assurance of meeting DO criteria in the lake's sub-epilimnetic waters.

During periods of thermal stratification in a lake, DO concentration below the epilimnion is largely determined by the relationship between trophic status and the saturation potential of oxygen. Because DO concentration is a function of temperature, the minimum allowable DO concentration cannot be specified *per se*, but can be determined graphically by reading the expected DO concentration at a specified percent saturation from a published nomogram.

Chapra (1997) presents ranges of hypolimnetic DO saturation as a function of trophic status in eutrophic, mesotrophic and oligotrophic lakes (Table A-4). MDE (1999) has adapted and extended this methodology to apply to the two additional trophic categories—oligo-mesotrophic and meso-eutrophic—used to classify Maryland's lakes (Table A-5).

**Table A-4**

### **Relationship between Lake Trophic Status and Dissolved Oxygen Saturation in the Hypolimnion of a Thermally Stratified Lake**

<b>Trophic Status</b>	<b>Hypolimnetic Dissolved Oxygen Saturation</b>
<b>Eutrophic</b>	0% - 10%
<b>Mesotrophic</b>	10% - 80%
<b>Oligotrophic</b>	80% - 100%

Adapted from Chapra (1997)

**Table A-5**

### **Extended Relationship between Lake Trophic Status and Dissolved Oxygen Saturation in the Sub-Epilimnetic Waters of a Thermally Stratified Lake**

<b>Trophic Status</b>	<b>Minimum Hypolimnetic Dissolved Oxygen Saturation</b>
<b>Eutrophic</b>	0%
<b>Meso-eutrophic</b>	10%
<b>Mesotrophic</b>	33%
<b>Oligo-mesotrophic</b>	56%
<b>Oligotrophic</b>	80%

MDE is establishing a phosphorus TMDL to manage Lake Habeeb at the oligo-mesotrophic status. Current phosphorus loading estimates place Lake Habeeb slightly in the eutrophic range. As phosphorus reductions result in a shift to an oligo-mesotrophic status, it is predicted that the DO saturation will increase to a range of 56% in the waters below the epilimnion, as indicated in Table A-5. This increased saturation is consistent with interim interpretation of Maryland's water quality criterion for dissolved oxygen in thermally stratified lakes (MDE, 1999).

Because DO concentration is a function of water temperature, a single expected DO concentration cannot be predicted. However, the nomogram in Figure A-2 may be used to determine a range of dissolved oxygen concentrations expected to result as phosphorus loads are reduced. This is demonstrated below using temperatures observed in the deeper waters of Lake Habeeb during critical summertime conditions.

Specifically, two line segments have been drawn from the ends of the observed range of temperatures (6.8 - 23°C), through the point at 56% on the diagonal scale for DO saturation. These two line segments intersect the lower horizontal scale indicating an expected DO concentration ranging from 4.8 – 6.8 mg/l. This range reflects an increase over the current minimum observed DO concentration of 0.1 mg/l, and reflects the DO endpoint expected to result from the TMDL. This increased sub-epilimnetic DO concentration is consistent with the interim interpretation of Maryland's water quality criterion for dissolved oxygen in thermally stratified lakes (MDE, 1999).

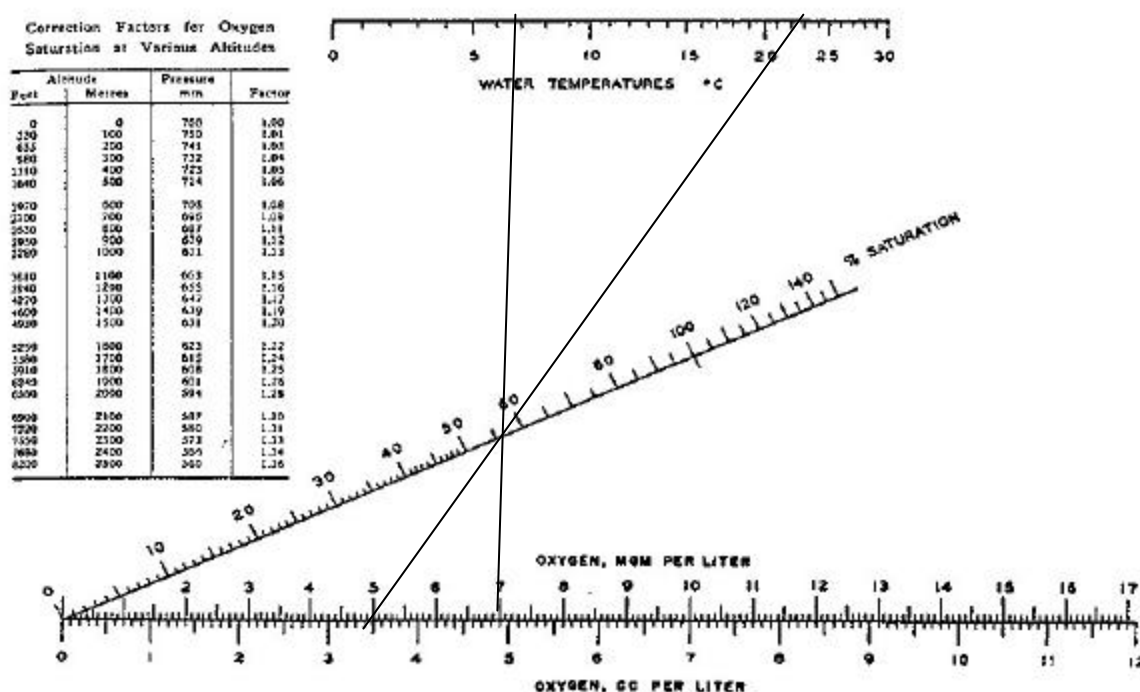


Figure A-2. Nomogram (adapted from Reid 1961) showing expected sub-epilimnetic DO concentrations at ambient temperatures in Lake Habeeb during periods of stratification.